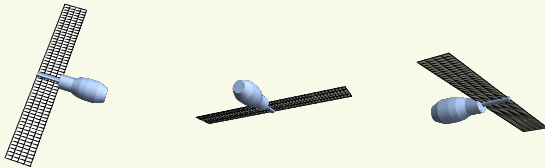


Recreating *in situ* measurements of potentially hazardous meteoroids

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Outline

- ▶ Damage equations/BLEs
- ▶ Meteoroid model: MEM 3
- ▶ *In situ* experiments
 - ▶ Pegasus
 - ▶ LDEF
- ▶ *In situ* constraints on the speed distribution?

Ballistic limit equations (BLEs)

modified Cour-Palais BLE

BLEs describe the extent of damage caused by an impact.

modified Cour-Palais (CP) BLE:

$$p_t = 5.24 d^{19/18} BH^{-1/4} \left(\frac{\rho}{\rho_t} \right)^{1/2} \left(\frac{v_{\perp}}{c_t} \right)^{2/3}$$

extent of damage	meteoroid properties	target properties
p_t = crater depth	d = diameter ρ = density v_{\perp} = normal speed	BH = Brinell hardness ρ_t = density c_t = sound speed

Ballistic limit equations (BLEs)

modified Cour-Palais BLE

$$p_t = 5.24 d^{19/18} B H^{-1/4} \left(\frac{\rho}{\rho_t} \right)^{1/2} \left(\frac{v_{\perp}}{c_t} \right)^{2/3}$$

CP BLE is widely used because ...

- ▶ it's simple
- ▶ it's separable
- ▶ can compute in log-space
- ▶ it's invertible

Ballistic limit equations (BLEs)

Watts & Atkinson (WA)

BLEs can be **considerably** more complex ...

crater diameter:

$$d_0 = 1.3235 d (c_t/c)^{2/7} (v_{\perp}/v_0)^{4/7}$$

$$f = \left(1 + \sqrt{2\Delta/d_0}\right)^{-1/3}$$

$$d_t = f \cdot d_0$$



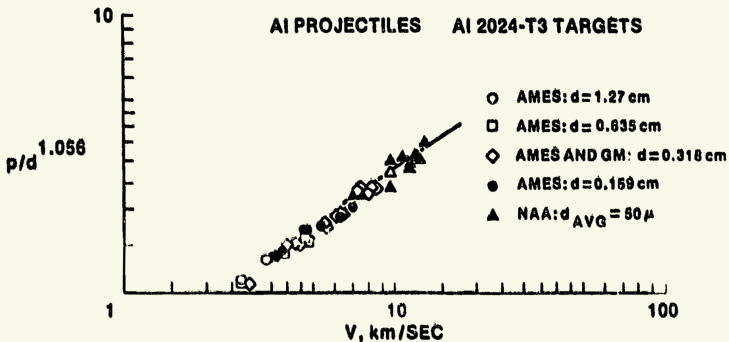
crater depth:

$$p_t = \frac{fd}{4} \left(\frac{4}{3} \frac{\rho}{Y_t} \left(c_{0,t} + \frac{s(v_{\perp} - v_0)}{1 + \sqrt{\rho_t/\rho}} \right) (v_{\perp} - v_0) \right)^{1/3}$$

penetration thickness:

$$t_t = \frac{fd}{4} \left(\frac{1}{6} \frac{\rho}{Y_t} \left(c_{0,t} + \frac{s(v_{\perp} - v_0)}{1 + \sqrt{\rho_t/\rho}} \right) (v_{\perp} - v_0) \right)^{1/3} + \frac{fd}{4} \frac{v_{\perp}}{v_0} \sqrt{\frac{Y_t}{\sigma_t}}$$

BLE uncertainties



- ▶ CP BLE derived from Al-on-Al impacts at relatively low speeds
- ▶ scatter is $\lesssim 30\%$
- ▶ behavior at high speeds?
- ▶ behavior for non-metal particles?

Weighting to a constant limiting crater diameter

Meteoroid models are often mass-limited. A scaling relation is needed to adjust the flux level:

$$\text{flux}_{\text{effect}} = \sum_{i,j,k,n} \text{flux}_{i,j,k,n}(m_{\text{run}}) \times \frac{g(m_{\text{effect}}(\phi_i, \theta_j, v_k, \rho_n))}{g(m_{\text{run}})}$$

m_{effect} comes from your BLE:

$$\frac{d}{1 \text{ cm}} = \left[\frac{p_t}{5.24 \text{ cm}} h^{1/4} \left(\frac{\rho}{\rho_t} \right)^{-1/2} \left(\frac{v_{\perp}}{c_t} \right)^{-2/3} \right]^{18/19}$$
$$m = \pi \rho d^3 / 6$$

NASA Meteoroid Engineering Model (MEM), version 3

MEM 3

File Help

Input options

Input file: Z:\Documents\ISSEExample.txt ...
Vectors in input file: 10

Input origin: Earth

Input axes: equatorial

Run options

Vectors used: all

Vector count (n): 10

Limiting mass: -6
Enter log base 10 of mass in grams

☐ High fidelity mode

Output options

Location: Z:\Documents ...

Run name: MyRun

Output origin: Sun

Output axes: body-fixed

Angular resolution (degrees): 5

Velocity resolution (km/s): 1

☐ Output intermediate files

☐ Output threat igloo files

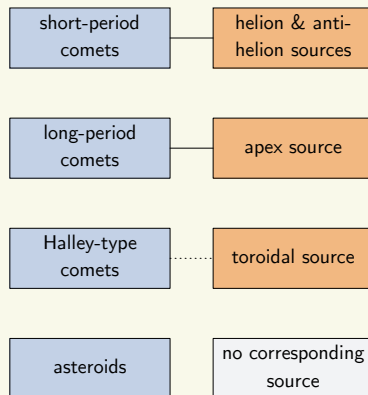
☐ Output standard deviation files

Calculate **Abort** **Results**

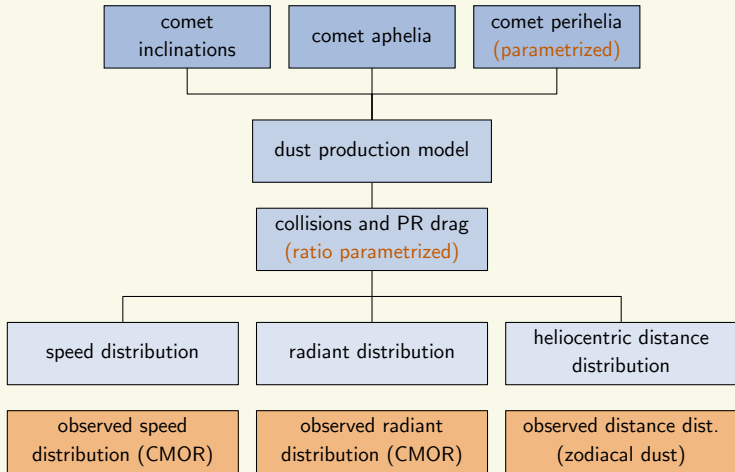
MEM model found Estimated Space: 1.55 MB Disk free space: 447.75 GB 40% Complete Time remaining: 13s

Jones (2004)

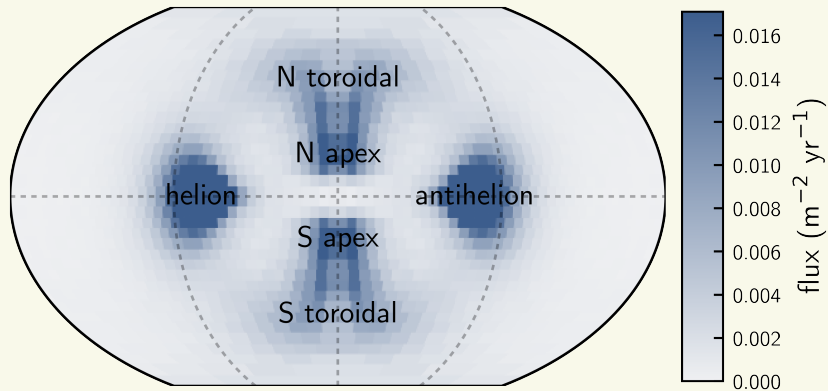
- ▶ MEM ...
 - ▶ is *not* purely empirical
 - ▶ is *not* an N-body simulation
 - ▶ *is* an analytic, physics-based model calibrated to match observations
- ▶ Jones (2004) linked parent populations to observed distributions, taking radiative forces and collisions into account
- ▶ Physical model mostly the same since 2004



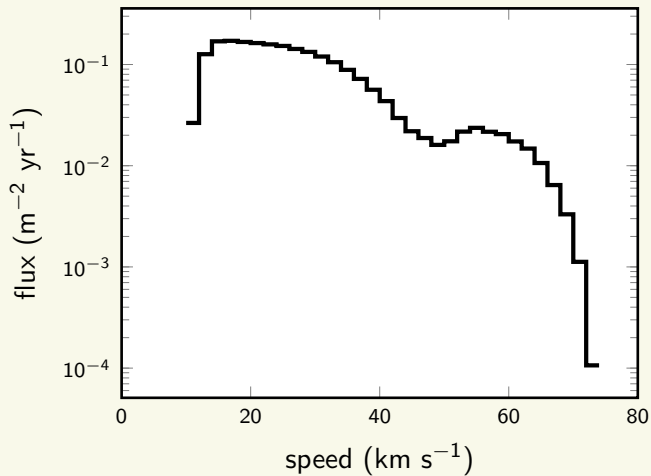
Jones (2004)



Radiant distribution

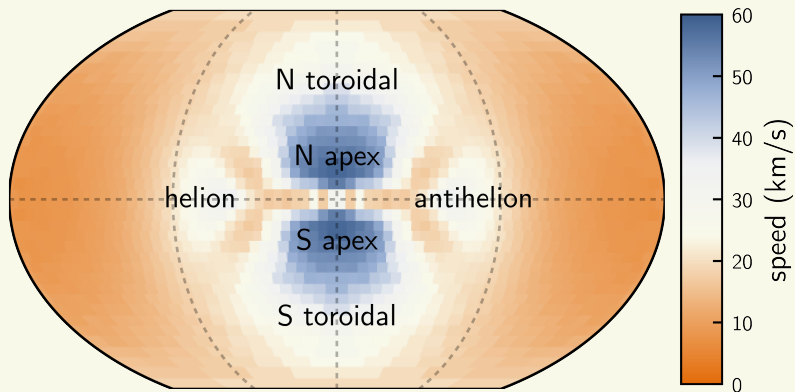


Speed distribution

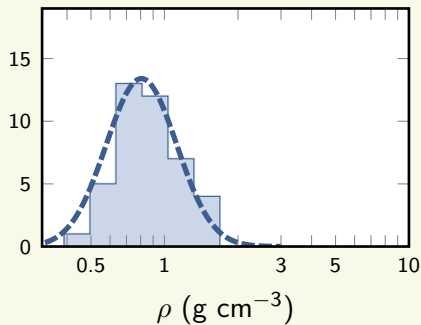
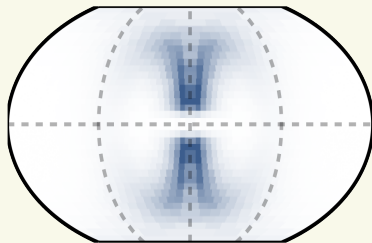
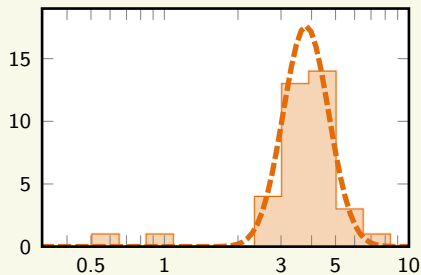
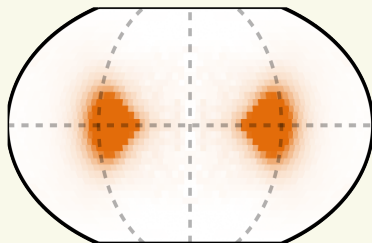


Velocity distribution

$$\frac{d}{d\theta} \frac{d}{d\phi} \frac{dF}{dv} \neq \frac{1}{F} \frac{dF}{d\theta} \times \frac{1}{F} \frac{dF}{d\phi} \times \frac{dF}{dv}$$

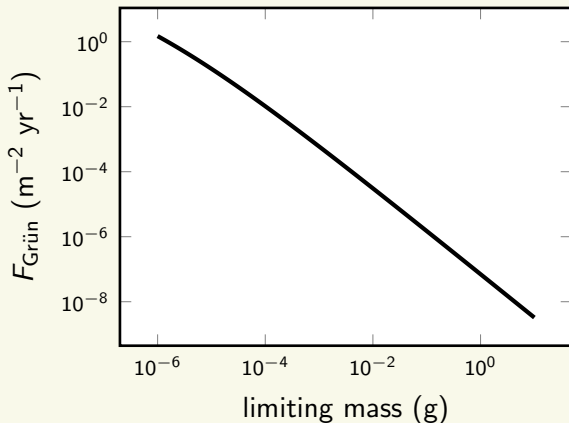


Density distribution



Mass scaling

MEM uses Grün et al. (1985) flux equation to scale to arbitrary limiting mass:



Ready to calculate damaging flux!

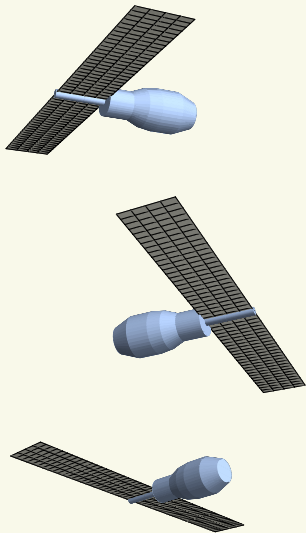
At this point, we have all needed elements to calculate damage-limited flux:

$$m_{\text{effect}} = \frac{\pi \rho_n}{6} \left[\frac{p_t}{5.24} h^{1/4} \left(\frac{\rho_n}{\rho_t} \right)^{-1/2} \left(\frac{v_{\perp}(v_k, \phi_i, \theta_j)}{c_t} \right)^{-2/3} \right]^{54/19}$$

$$\text{flux}_{\text{effect}} = \sum_{i,j,k,n} \text{flux}_{i,j,k,n}(m_{\text{run}}) \times \frac{g(m_{\text{effect}}(\phi_i, \theta_j, v_k, \rho_n))}{g(m_{\text{run}})}$$

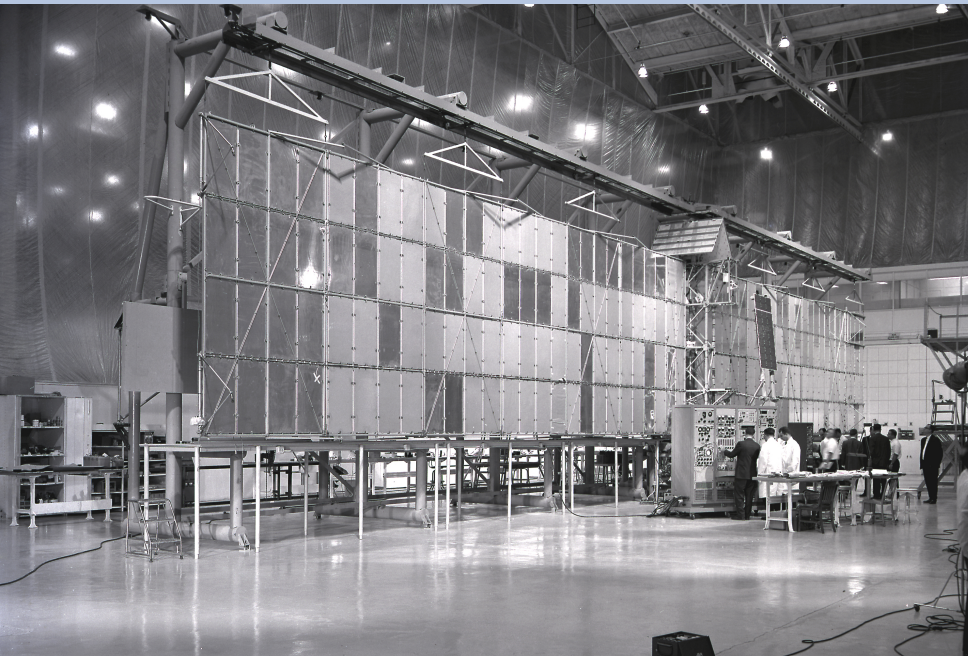
- ▶ Orange quantities provided by MEM
- ▶ Blue quantities depend on spacecraft surface
- ▶ Green quantity is determined by effect

Pegasus



- ▶ **Year(s) data collected:**
1965
- ▶ **Detection method:**
penetration detectors
- ▶ **Relevant area:**
over 200 m² (0.4 mm panels)
- ▶ **Attitude:**
attitude information lost
(assume randomly tumbling)
- ▶ **Material:**
2024-T3 Al alloy

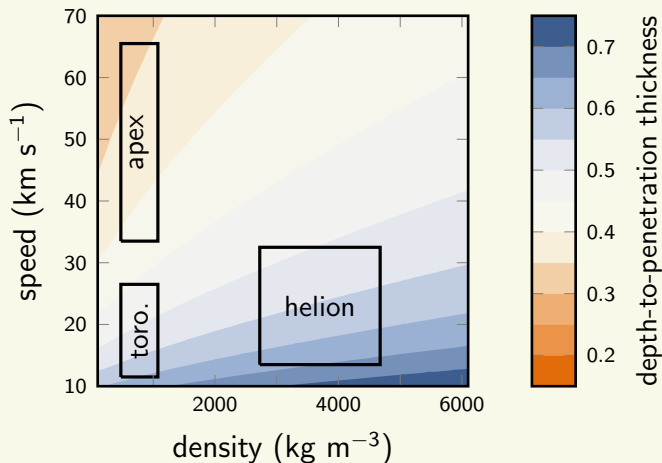
Pegasus



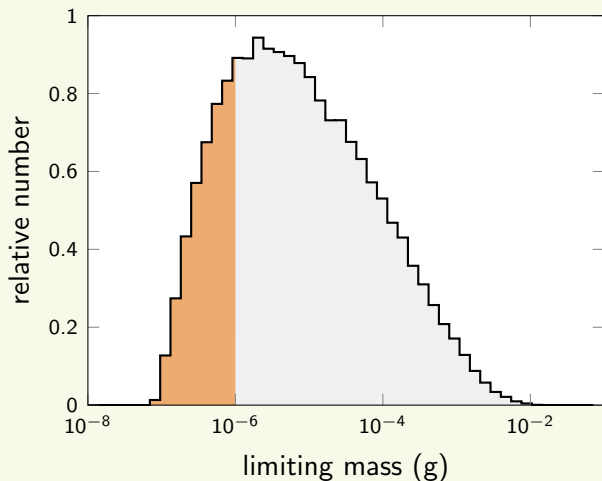
Pegasus: limiting penetration thickness

Cour-Palais: $p/t = 1/1.8 = 0.\bar{5}$

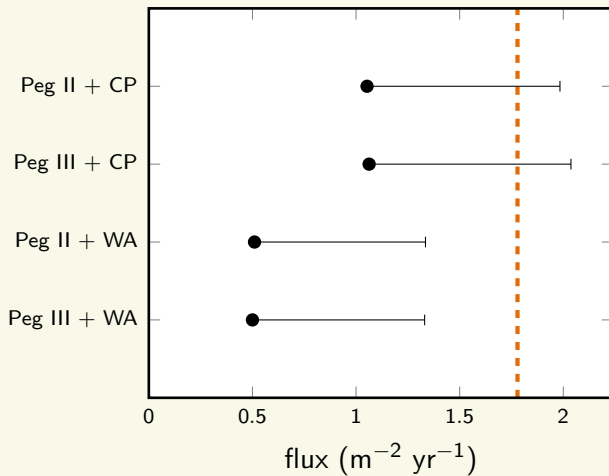
Watts & Atkinson:



Pegasus: limiting masses



Pegasus results



Long Duration Exposure Facility (LDEF)

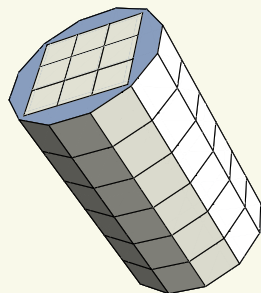
NASA
National Aeronautics and
Space Administration

Long Duration Exposure Facility (LDEF)

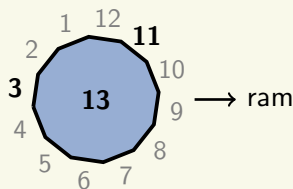


- ▶ **Year(s) data collected:**
1984 – 1990
- ▶ **Detection method:**
examination of panels
- ▶ **Relevant area:**
 10.8 m^2
- ▶ **Attitude:**
constant relative to orbit
- ▶ **Material:**
6061-T6 Al alloy

Long Duration Exposure Facility (LDEF)



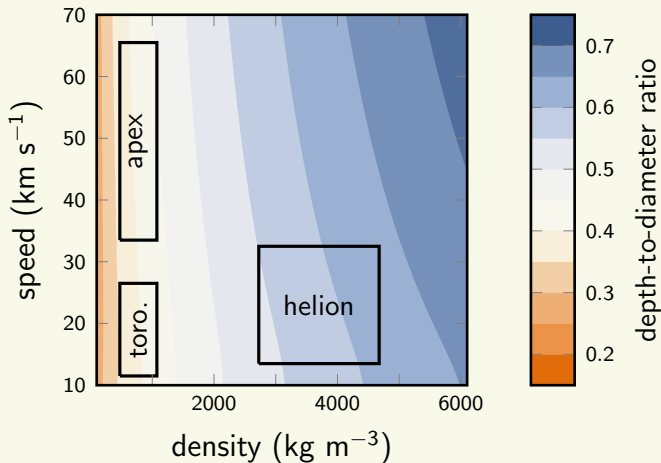
- ▶ Interested in largest craters ($100\text{ }\mu\text{m}$)
- ▶ Significant orbital debris present
- ▶ Orbital debris estimate available on three sides from smaller craters on CME



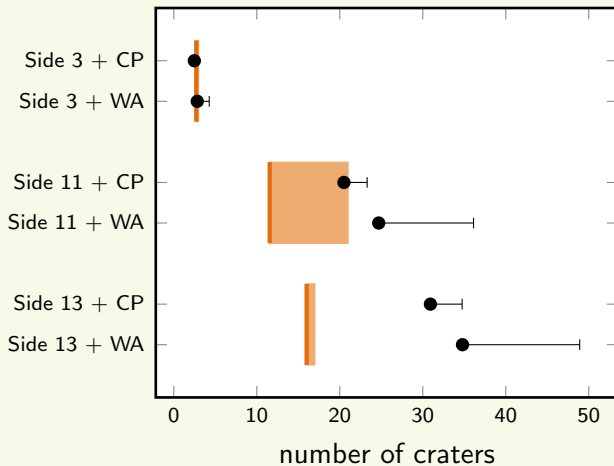
LDEF: depth-to-diameter ratio

Cour-Palais: $p/d = 0.5$ (based on observed morphology)

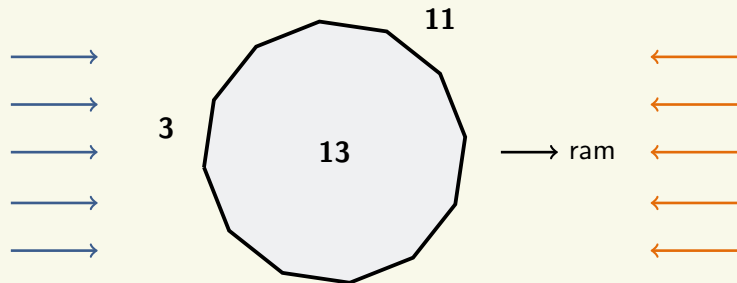
Watts & Atkinson:



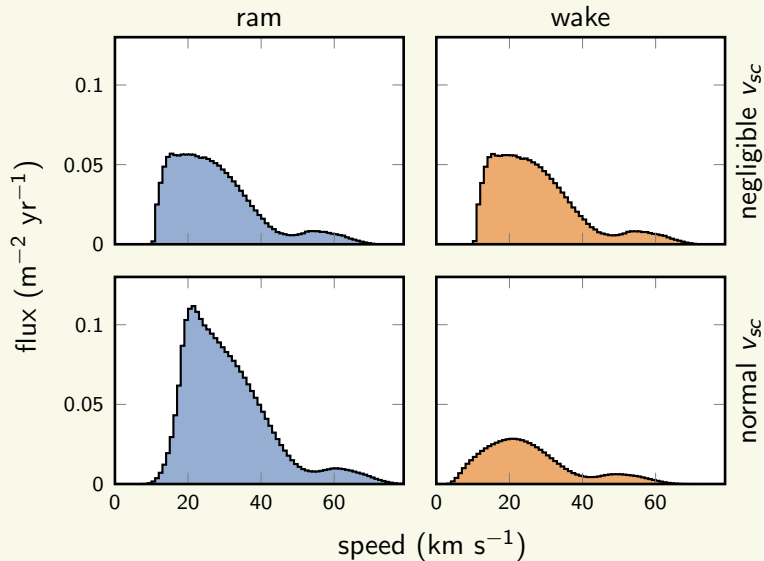
LDEF results



Constraints on speed distribution?

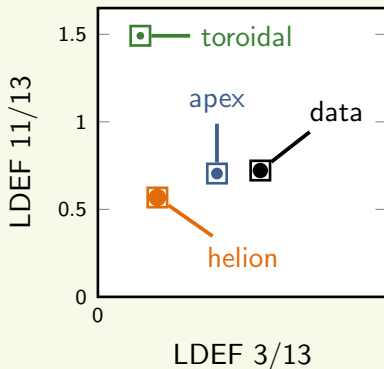


Effect of spacecraft velocity on flux

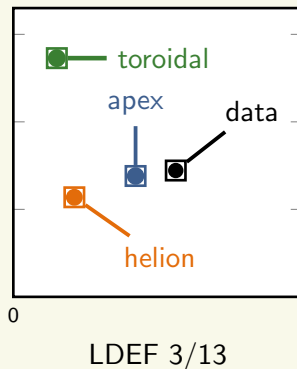


Crater ratios

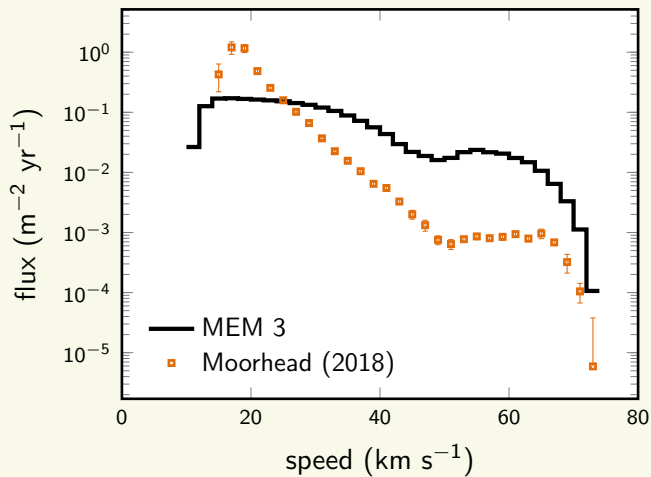
MEM 3 + CP



MEM 3 + WA



Speed distribution measurements



Summary

- ▶ BLEs relate impact parameters to damage
- ▶ BLEs can be combined with meteoroid model to predict damage/risk
- ▶ We have combined MEM 3 with two BLEs (Cour-Palais, Watts & Atkinson) for:
 - ▶ Pegasus: predictions too low
 - ▶ LDEF: predictions too high
- ▶ Comparing the crater counts on different sides of LDEF constrains the speed distribution in theory, but the results are in conflict with meteor observations